

THE AXINO-GRAVITINO COSMOLOGY

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A cosmological scenario of a light axino and a lighter gravitino is presented^{1,2}. The most important consequence is that it can mimick the mixed dark matter (MDM) model of the large scale structure formation. The presence of axino and gravitino is inevitable in supergravity extension of the invisible axion solution of the strong CP problem. The possibility of a light gravitino is popular in the recent efforts of gauge mediated supersymmetry breaking.

1 Introduction

The minimal standard model contains 19 free parameters. Among these the parameters θ_{QCD} and the Higgs boson mass are of most fundamental importance which have led to

- strong CP problem and axions,
- gauge hierarchy problem, supersymmetry, etc.

The parameter problem is generally requiring an understanding of WHY the parameter takes the value chosen by nature.

Here I will discuss one scenario for the dark matter arising from the attempt to solve the above parameter problems: axion, supersymmetry, axino and gravitino.

2 The θ_{QCD} Parameter Problem

Quantum chromodynamics before 1975 was described by

$$\mathcal{L} = -\frac{1}{2g^2} \text{Tr} F_{\mu\nu} F^{\mu\nu} + \bar{q}(iD^\mu \gamma_\mu - M)q. \quad (1)$$

After 1975, it has been known to be inevitable to include, due to the discovery of the instanton configuration³,

$$+ \frac{\bar{\theta}}{16\pi^2} \text{Tr} F_{\mu\nu} \tilde{F}^{\mu\nu}. \quad (2)$$

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It must be included if there is no massless quark. This $\bar{\theta}$ term is a total divergence, but the gauge field configuration at infinity gives a nontrivial surface term. Thus $\bar{\theta}$ parameter is physical and strong interactions violate the CP symmetry. From the upper bound of neutron electric dipole moment $|d_n|_{\text{exp}} < 1.2 \times 10^{-25} \text{ ecm}^4$, we obtain a bound on $\bar{\theta}$

$$|\bar{\theta}| < 10^{-9}. \quad (3)$$

The essence of the strong CP problem is, “Why is $\bar{\theta}$ so small?” The most attractive solution of the strong CP problem is the axion solution. The history of axion is

- 1997: The Peccei-Quinn symmetry⁵ and PQWW axion⁶
- 1978: No PQWW axion⁷ and calculable models⁸
- 1979: Invisible axion⁹
- 1984: Superstring axion¹⁰
- 1985: Composite axion¹¹
- 1988: Anomalous $U(1)$ axion¹²

These axion models introduce a pseudoscalar field a in the effective Lagrangian. One can show that $\bar{\theta} = 0$ is the minimum of the free energy from the simple and elegant argument regarding the pseudoscalar nature of the $F\tilde{F}$ term¹³. After integrating out the quark fields, one obtains the following path integral in the Euclidian space,

$$\int [dA_\mu] \prod_i \text{Det}(D^\mu \gamma_\mu + m_i) e^{-\int d^4x (\frac{1}{4g^2} F^2 - i\bar{\theta} \{F\tilde{F}\})} \quad (4)$$

where $\{ \}$ includes the factor $1/32\pi^2$. Note that the $\bar{\theta}$ term is pure imaginary in the Euclidian space. In the Euclidian space, $\text{Det}(D^\mu \gamma_\mu + m_i) > 0$. Therefore, defining the integral as a function of $\bar{\theta}$, we obtain the following inequality, due to the Schwarz inequality,

$$\begin{aligned} e^{-\int d^4x V[\bar{\theta}]} &\equiv \int [dA_\mu] \prod_i \text{Det}(D^\mu \gamma_\mu + m_i) e^{-\int d^4x (\frac{1}{4g^2} F^2 - i\bar{\theta} \{F\tilde{F}\})} \\ &\leq \int [dA_\mu] \left| \prod_i \text{Det}(D^\mu \gamma_\mu + m_i) e^{-\int d^4x (\frac{1}{4g^2} F^2 - i\bar{\theta} \{F\tilde{F}\})} \right| \\ &= e^{-\int d^4x V[0]} \end{aligned} \quad (5)$$

which implies

$$V[\bar{\theta}] \geq V[0]. \quad (6)$$

Thus we obtain that $\bar{\theta} = \langle a \rangle / F_a = 0$ is the minimum of the axion potential. In the above proof, we neglected the weak CP violation. Inclusion

of the weak CP violation shifts the position of the minimum but not very much¹⁴.

This potential is almost flat for a large F_a . Thus the classical axion field starts to oscillate very late, $T \sim 1$ GeV, measured at the scale of F_a , which leads to the significant cold axion energy density in the universe¹⁵.

3 Axino-gravitino Cosmology

Supersymmetrization of axion introduces s (saxion, the scalar partner of a) and \tilde{a} (axino, the fermionic partner of a). Mass of s is of order M_{SUSY} . But the axino mass can be lighter. It depends on models¹⁶. With the presence of the axino, it is important to know what is the LSP with the unbroken R -parity. The cosmological scenario with (\tilde{a} = LSP) has been studied extensively by Rajagopal *et al.*¹⁷.

The case with (gravitino = LSP) arises in no-scale supergravity models¹⁸ and in the gauge mediated SUSY breaking scenario¹⁹. Phenomenological applications of the gravitino LSP are the axino-gravitino cosmology¹ and the anomalous γ event of the CDF group. The axion–axino–gravitino coupling is given by

$$\mathcal{L}_{a\tilde{a}\tilde{G}} = \frac{1}{M_P} \bar{\psi}_\mu \gamma^\nu \partial_\nu z^* \gamma^\mu \tilde{a}_L + \text{h.c.} \quad (7)$$

where $z = (s + ia)/\sqrt{2}$ and $M_P \simeq 2.44 \times 10^{18}$ GeV. For the light gravitino, the Goldstino component ξ dominates and replacing $\psi_\mu = i\sqrt{2/3}(1/m_{3/2})\partial_\mu \xi$ gives the lifetime of axino from the $\tilde{a} \rightarrow \tilde{G} + a$ decay as^{1,2}

$$\tau_{\tilde{a}} = \frac{96\pi M_P^2 m_{3/2}^2}{m_{\tilde{a}}^5} \simeq 1.2 \times 10^{12} \left(\frac{\text{MeV}}{m_{\tilde{a}}} \right)^5 \left(\frac{m_{3/2}}{\text{eV}} \right)^2 \text{ sec.} \quad (8)$$

The decoupling temperature of \tilde{a} is¹⁷

$$T_{\tilde{a}} = 10^{11} \left(\frac{F_a}{10^{12} \text{ GeV}} \right)^2 \left(\frac{0.1}{\alpha_c} \right)^3 \text{ GeV.} \quad (9)$$

So it is interesting to note that the MeV axino mass with low energy SUSY breaking leads to the axino lifetime around the time of galaxy formation. This axino may affect the formation of large scale structures.

3.1 Cosmology with late decaying particles

The cold dark matter (CDM) was successful before the COBE data. This assumes a flat universe with 5–10 % baryonic dark matter and the rest CDM.

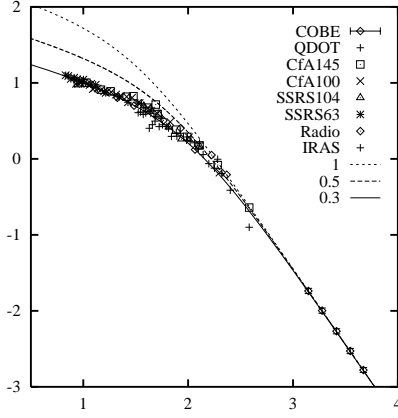


Figure 1: $\log_{10} \frac{\delta \rho}{\rho}$ versus $\log_{10} \frac{\lambda}{h^{-1} \text{Mpc}}$.

The seed fluctuations with the inflationary idea are assumed to be of the scale invariant form. In this case the evolved spectrum is given by²⁰

$$|\delta_k|^2 = \frac{Ak}{(1 + \alpha k + \beta k^{3/2} + \gamma k^2)^2} \quad (10)$$

where A is a normalization constant, $\alpha = 1.7l$, $\beta = 9.0l^{3/2}$, $\gamma = 1.0l^2$, and

$$l = (\Omega h^2)^{-1} \theta^{1/2} \text{ Mpc}. \quad (11)$$

Here $\theta = \rho_{\text{rel}}/1.68\rho_\gamma$ measuring the present energy density of all relativistic particles relative to those of photons and neutrinos. The COBE data fixed the normalization, and the CDM model needed modifications.

Successful fits are: (i) $\Omega_\Lambda \simeq 0.8$ and $\Omega_{\text{CDM}} \simeq 0.2$, (ii) $\Omega_{\text{CDM}} \simeq 0.7$ and $\Omega_{\text{HDM}} \simeq 0.3$, and (iii) $\Omega_{\text{CDM}} = 0.2 - 0.3$. One can mimic Case (iii) even in the $\Omega = 1$ universe if $\theta \neq 1$. In effect, it resembles a CDM+HDM universe (\equiv MDM). The $\theta > 1$ universe is obtained in cosmology with late decaying particles. The decay products must be relativistic and noninteracting to mimic Case (iii). The late decaying particle cosmology was first considered by Bardeen, Bond and Efstathiou²⁰, then applied for the by-now dead 17 keV neutrino by Bond and Efstathiou²¹. After the COBE data, it was first considered by Chun *et al.*¹, and this idea was later applied to ν_τ by others²². For the

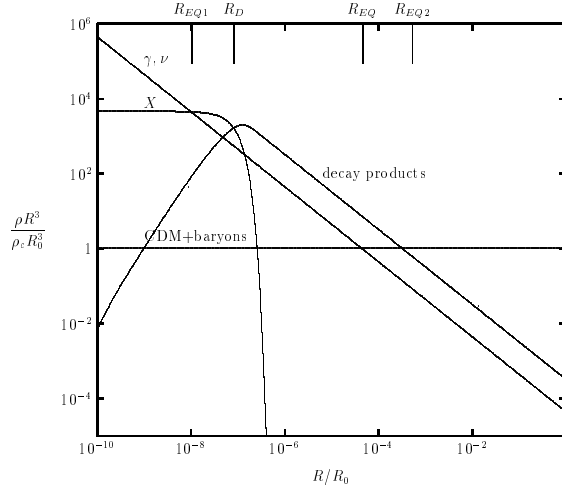


Figure 2: Scale factor versus energy densities of particles.

structure formation, the radiation-matter equality point R_{EQ} is important. At R_{EQ} the structure scale λ_{EQ} is given by

$$\lambda_{EQ} \simeq 30(\Omega h^2)^{-1} \theta^{1/2} \text{ Mpc.} \quad (12)$$

3.2 Axino-gravitino cosmology

A light axino decays to an axion and a gravitino via the interaction given in Eq. (7). Normally, one would expect a coupling suppressed by M_P , but the Goldstino component dominates whose coupling is suppressed by F_S . Namely, the gravitino coupling is of the form $(1/F_S)(\partial_\mu \xi)J^\mu$ where J^μ is the supercurrent. In this case, the axino lifetime is given in Eq. (8). The detail energy densities of respective species are given in Fig. 2.

When the cosmic scale factor exceeds R_{EQ1} , \tilde{a} dominates the mass density of the universe. The cold axion dominates the energy density of the universe after the scale factor exceeds R_{EQ2} . In Fig. 3, R_{EQ} is the radiation-matter equality point in the CDM model. Thus, the axino-gravitino cosmology extends the time for R_{EQ} by a factor

$$\frac{R_{EQ2}}{R_{EQ}} \simeq 1 + \left(\frac{\tau_{\tilde{a}}}{t_{EQ1}} \right)^{2/3} \quad (13)$$

compared to the CDM model. Roughly, the fluctuation spectrum is characterized by two length scales,

$$\begin{aligned}\lambda_{EQ1} &\simeq 8 \times 10^{-2} \left(\frac{\text{MeV}}{m_{\tilde{a}} Y} \right) \\ \lambda_{EQ2} &\simeq 30(\Omega h^2)^{-1} \left[1 + \left\{ \frac{1}{0.55} \left(\frac{\tau_{\tilde{a}}}{\text{sec}} \right) \left(\frac{m_{\tilde{a}} Y}{\text{MeV}} \right)^2 \right\}^{2/3} \right]^{1/2}\end{aligned}\quad (14)$$

kpc where $Y = n_{\tilde{a}}(T)/s(T)$. λ_{EQ2} corresponds to the size of galaxies, and it is interesting if λ_{EQ1} corresponds to the size of globular clusters. The condition that the axino model mimicks the mixed dark matter model in the $\Omega = 1$ universe is

$$\left(\frac{\tau_{\tilde{a}}}{\text{sec}} \right) \left(\frac{m_{\tilde{a}} Y}{\text{MeV}} \right)^2 \simeq 0.55 \left[\left(\frac{h}{0.2} \right)^2 - 1 \right]^{3/2}. \quad (15)$$

The nucleosynthesis bound is

$$\left(\frac{m_{\tilde{a}} Y}{\text{MeV}} \right) < 0.107 \quad \text{for } m_{\tilde{a}} > 1 \text{ MeV}. \quad (16)$$

The energy density bound is

$$\left(\frac{\tau_{\tilde{a}}}{\text{sec}} \right) \left(\frac{m_{\tilde{a}} Y}{\text{MeV}} \right) < 2 \times 10^6 h^3. \quad (17)$$

These conditions are shown in Fig. 3.

The size λ_{EQ1} depends on the reheating temperature T_R . If $T_R \gg T_{\tilde{a}}$, then one obtains $\lambda_{EQ1} \sim 44(\text{MeV}/m_{\tilde{a}})$ kpc. If $T_R \ll T_{\tilde{a}}$, then $\lambda_{EQ1} \sim 11(F_a/10^{12} \text{ GeV})^2 (10^6 \text{ GeV}/T_R) (\text{GeV}/m_{\tilde{a}})^2$ kpc. The dotted line in Fig. 3 is Eq. (15).

4 Conclusion

The simultaneous solution of the strong CP problem and the gauge hierarchy problem leads to axino and gravitino. The LSP is probably the axino or the gravitino. If the gravitino is the LSP, its effect on the large scale structure formation can mimic the MDM for appropriate mass parameters of the axino and gravitino. And there may be smaller size (\sim tens of kpc) structures also.

Acknowledgments

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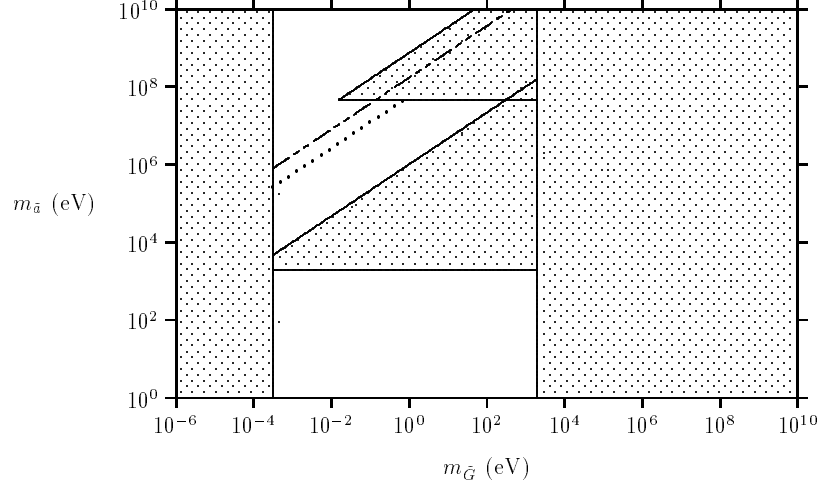


Figure 3: Exclusion plot in the axino and gravitino mass plane.

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